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ENERGY MODELS AND LARGE-SCALE SYSTEMS OPTIMIZATION. (U)

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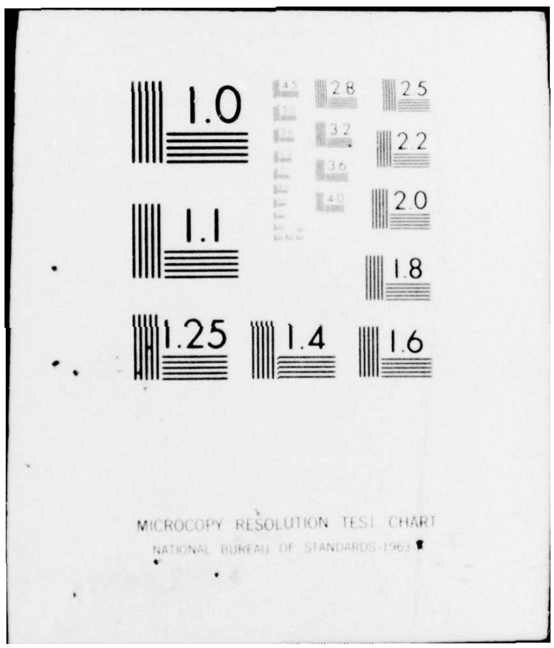
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BY

GEORGE B. DANTZIG and SHAILENDRA C. PARIKH

TECHNICAL REPORT SOL 76-23

NOVEMBER 1976

Systems Optimization Laboratory

Department of Operations Research

Stanford University

Stanford California 94305

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SYSTEMS OPTIMIZATION LABORATORY

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ENERGY MODELS AND LARGE-SCALE SYSTEMS OPTIMIZATION*

George B. Dantzig and Shailendra C. Parikh
Stanford University

The optimization of large-scale dynamic systems represents a central area of research whose successful outcome could make important contributions to the analysis of crucial national and world problems. Although a great number of papers have been published on the theory of solving large-scale systems, not much in software exists that can successfully solve such systems. We believe that there has been little progress, because there has been little in the way of extensive experimentation comparing methods under laboratory-like conditions on representative models. At Stanford's Systems Optimization Laboratory (SOL), to bridge this gap between theory and application, we

(1) develop experimental software for solving large-scale dynamic systems,
(2) systematically compare proposed techniques on representative models,
(3) record and disseminate information regarding experimental results.

PILOT Energy-Economic Model

Dynamic models that describe the interactions between the energy sector and the general economy help in providing a focus to our research in experimenting with large-scale optimization models. Models of this type are under development by a number of groups to study the energy crisis and a probable future crisis in the area of food (agriculture). Developers of these models could make effective use of techniques for solving large-scale systems, if they were available.

Today's policy makers at industrial, governmental and international levels are faced with the decisions on providing the needed energy in the years to come at acceptable social cost. Such decisions must take into account many complex interactions related to the technology of energy supply, environmental side effects, energy resource conservation, etc., as well as the national welfare considerations of unemployment, inflation and living standards.

Some of the important questions that must be considered in detail in the formulation of the energy policy (or policies) are the following:

(1) Are we using up our cheap energy resources too quickly?
(2) Are we making sufficient investments now so that new energy technologies will come into commercial operation when needed in future years?
(3) Do we have sufficient physical capacity to build the required new plant and equipment in the energy and nonenergy sectors without seriously hampering growth in consumer consumption, or will some sacrifice in consumption be necessary?
(4) What are the various energy options under different patterns of crude oil import price realizations?
(5) What will the short and long term impact be if oil and gas discoveries are less than predicted?
(6) Can we find an energy policy that is robust, i.e., one which hedges against various contingencies?

It is our belief that dynamic mathematical programming models can, at the very least, provide analysis and information on these and other questions and can substantially improve the understanding of the interactions that must be considered. Such models have been developed at IIASA, at the Electricité de France and by various groups in the United States.

In the Systems Optimization Laboratory at Stanford we have under development a linear programming model for assessing energy-economic options in the United States, called PILOT [7]. It spans a wide spectrum of activities of the economy, from exploration and extraction of raw energy to industrial production and consumer demands for all goods and services. The data requirements therefore cut across many different sources--consumer surveys, import/export and trade balance data, manufacturers surveys, mining data, input/output

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and capital coefficients, energy consumption and substitution data, energy technology data from Brookhaven National Laboratory and oil and gas exploration and production data. Hence, there is a nontrivial problem of achieving consistency and of selecting a meaningful level of detail so that the model stands as a whole rather than as a conglomeration of parts that could collapse under careful analysis. We believe that the initial version of the model being built will meet this test.

The PILOT model is a statement in physical flow terms, to the extent possible, of the broad technological interactions within and across the sectors of the economy, including, but in greater detail, the energy sector. A typical run of the model describes what the country could achieve in physical terms over the long term, say 40 years.

A preliminary version of the model has been completed and several useful scenarios have been run [16]. In 1977, improved versions of the model will be developed, with more detail regarding exploration and extraction by regions, more detailed modeling of various conversion processes, better representation of foreign trade, substitution, financial flows and the effect of prices on demand and production.

The initial version of the PILOT model is an eight period, 40 year model which has approximately 800 constraints and 2000 variables.

The model is a description in input/output terms of the industrial processes of the economy and the demands for consumption, capacity formation, government services and net exports. The description of the processes that provide useful energy to the economy constitutes the detailed energy submodel. This consists of technological input/output descriptions of the raw energy extraction and the energy conversion processes as well as the energy import and export activities. Four linkages interconnect the energy sector and the rest of the economy: energy demands of the economy, bill of goods needed for energy processing and capacity expansion, total manpower available to all sectors (including energy) and a trade balance constraint which requires the equating of total exports to total imports when these items are evaluated in 1967 dollars over successive five year periods. See Figure 1, which shows the major blocks of coefficients in a time period, and its link to the next time period show below and to the left of the dotted lines.

As noted earlier, the equations of the model express the balances of various physical flows. For the energy sector, the balances of coal, oil, gas, etc. are each expressed in BTU units. For the economy, the units are 1967 dollars, which are obtained by weighting the underlying physical flows of goods and services (assumed to be in fixed proportions) by 1967 prices per unit.

The industrial sectors of the economy are represented by a 23-order input/output matrix. The sectors are grouped as follows: 5 energy sectors, 1 agriculture, 1 nonenergy mining, 5 energy intensive manufacturing, 4 energy nonintensive manufacturing, 4 services and 3 capital formation.

Consumption is modeled in terms of the consumption vector of the average consumer. This sector does not have a fixed bill of goods per capita but varies as a function of a parameter representing the real consumption income attained per capita. Based on an analysis of historical data, consumption of any item as function of average consumption income is nearly linear [2].

Capacities for each of the 18 nonenergy sectors and all of the energy processes are differentiated from one another. The heterogeneous capital equipment of the nonenergy sectors is depreciated, whereas the energy facility capacities are assumed instead to have undepreciated, fixed lifetimes. Construction lags are used to specify the time it takes to build new capacity. These construction lags may be chosen individually for all 18 nonenergy sectors as well as for all energy facilities.

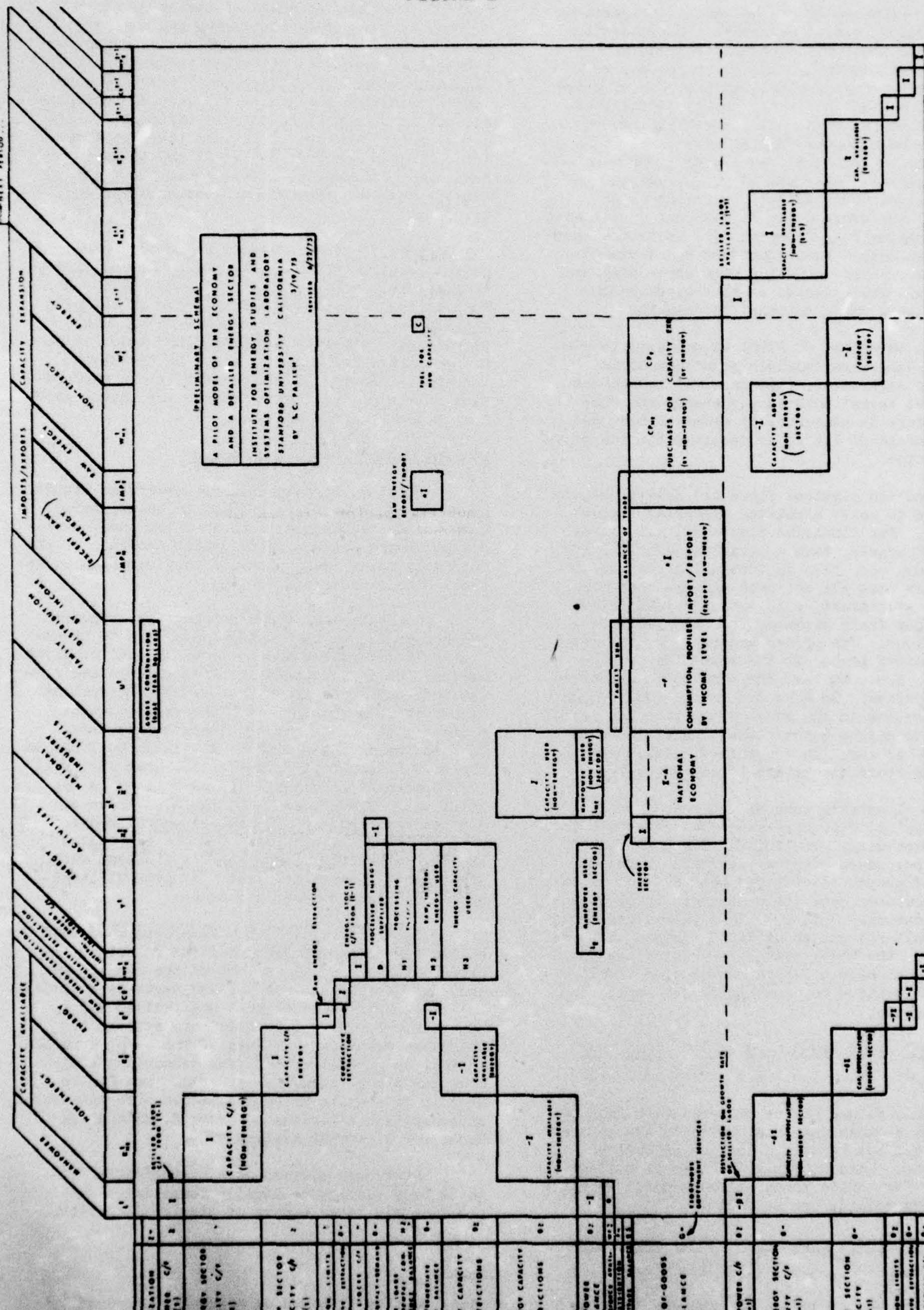
The exports are treated as final demand items. The imports are considered in two parts, competitive and noncompetitive. The noncompetitive imports are for those goods and services for which no domestic substitutes exist. They are treated as a part of the technology of the consuming industrial sector. On the other hand, competitive imports of goods and services for which domestic substitutes do exist are treated as activities that can augment the domestic production. Finally, a trade balance constraint ties together the amounts of all imports and exports. Typically, we have assumed over a five year period that the value of total exports be matched by that of imports.

The labor force is assumed to be exogenously given. Also, average labor productivity is assumed to grow at an exogenously given rate. In sample runs, the "standard of living" attained appears to be very sensitive to this factor. In the base case, 2% per year productivity growth is assumed.

The detailed energy sector contains the conventional energy technologies, such as oil refinery, coal fired plant, etc., as well as new technologies, such as coal synthetics, oil shale, plutonium fired reactors, etc.

The description of the energy sector includes an accounting of reserves remaining of three exhaustible energy resources: oil, gas and uranium. For oil and gas, finding-rate functions are used to specify the amount of oil in place and gas reserves to be found for a given amount of drilling effort. The level of drilling effort is endogenously determined. The advanced (and expansive) techniques of secondary and tertiary recovery are also defined in the model. Alaskan oil production and the Trans-Alaskan Pipeline System (TAPS) construction are assumed to be exogenously given. For natural uranium, increasing facilities and manpower are required to extract a ton of ore as more and more is extracted. In particular, progressively higher amounts of uranium mining and milling capacity are needed to process the poorer grade ore per pound of uranium oxide obtained. While, in principle, generalized linear programming could be used to model the nonlinear functions, we, in fact, replaced the nonlinear functions by broken line fits.

FIGURE 1



The PILOT model can be used in conjunction with any desired social objective. Consideration of reasonable alternative objectives requires further investigation. Some objectives may require their expression partly in the form of extra constraints as well as in the values of the coefficients of the maximand. The objective chosen in the base case in the initial version of the model is the undiscounted sum of the gross national consumption over all 40 years, subject to (1) a "monotonic per capita" constraint which states that the average per capita consumption must be nondecreasing over time, and (2) an initial condition which sets a lower limit on first period consumption. Experimentation with other maximands is possible. For example, we have experimented with discounted gross national consumption.

The objective of PILOT is designed to permit one to determine feasible solutions to our economy--in particular, what level of investment (in physical terms) both in the energy and non-energy sectors is necessary in order to have as high a standard of living as possible for the growing population.

Once the physical flows are determined, it is possible to solve a related financial investment model. The financial flow model calculates a system of prices, taxes, salaries, profits, interest rates, etc. that is internally consistent in the sense that all economic agents--consumers, producers, government, etc.,--receive sufficient monies to pay their expenses for the specified physical flows. The prices generated by the model can be adjusted to be, at the same time, noninflationary, i.e., to have the same buying power as base year prices. We also are giving some thought to incorporating in the model production and demand functions to adjust input/output coefficients as a function of prices. In the initial version of the model these coefficients are fixed, however.

To illustrate some of the output of the model, a typical base case assumes a 2% growth in labor productivity, 20% limit on the total amount of energy purchased overseas, certain limits on the rate of growth of coal production, etc. A base case run computes consumption income (income after taxes and savings). In 1975 this income per capita (in 1975 dollars) was about $4500. Based on these assumptions, the model states it is possible for the country to have a future consumption income per capita relative to consumption per capita in 1975 as follows:

1975	1980	1985	1990	1995	2000	2005	2010
1.0	1.0	1.2	1.6	1.7	1.8	2.0	2.2

This possible future can be compared with that obtained from another scenario, which is the same as the base case but restricts the use of nuclear power plants. This naturally results in a lower achievable per capita consumption income. Relative to 1975, the results are as follows:

1975	1980	1985	1990	1995	2000	2005	2010
1.0	1.0	1.2	1.5	1.5	1.5	1.5	1.5

Comparing the two scenarios at the year 2010, we have 2.2 vs. 1.5, i.e., the nuclear restriction could reduce the "standard of living" achievable by 2010 by 30%. This conclusion has been criticized because the model assumes that consumption patterns of people at different income levels will remain unchanged (i.e. they won't practice conservation or change their life styles) and that production methods will be no more efficient in the use of energy in the future than they are today. This criticism we feel has merit and we are, accordingly, considering revisions in the model to include more substitution and conservation possibilities.

Because of excellent liaison with other groups working in the energy field, we anticipate that the proposed physical flow model will contribute to the formulation and solution of the more detailed specialized models under development elsewhere. In particular, the PILOT model is one being compared with other models by the newly formed U.S. Energy Modeling Forum in its examination of the feedback effects from the energy sector on the economic growth.

Solving Multi-Time-Period Models*

Solving energy models by commercial linear programming software is proving to be expensive. Large-scale techniques, such as those under development at the Systems Optimization Laboratory, are currently under test to see if they can help solve these models more efficiently.

Conceptually, the decomposition principle [8] has proved to be a natural approach to breaking up large systems and to decentralized decision making. So far, computational experience has been limited, but it is known that several devices can be effectively combined with the decomposition principle to accelerate the iterative process. Classic research along these lines can be found in the work of Rosen [17], Beale [3], Gass [9], Bell [4], Abadie [1], Bennett [5], as well as in the joint work of Wolfe and Dantzig [8]. Areas of SOL research include (1) intertemporal models with staircase structures, (2) the continuous simplex method for linear control problems with state-space constraints, and (3) general large-scale dynamic nonlinear problems.

Recently, experiments have been conducted at SOL comparing the Decomposition Principle approach with a special variant of the simplex method known as Generalized GUB. These tests were limited in nature but indicated that Generalized GUB is superior. Our research on dynamic systems is therefore examining variants of the simplex method as well as special methods for decoupling staircase and block-triangular systems. See Figure 2. We plan to compare these approaches with the nested decomposition algorithm of James K. Ho and Alan S. Manne for staircase systems [12].

Staircase systems have historically proven to be very difficult, usually requiring a disproportionately large number of simplex iterations to solve.

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*This section is based on a summary prepared by J. A. Tomlin.

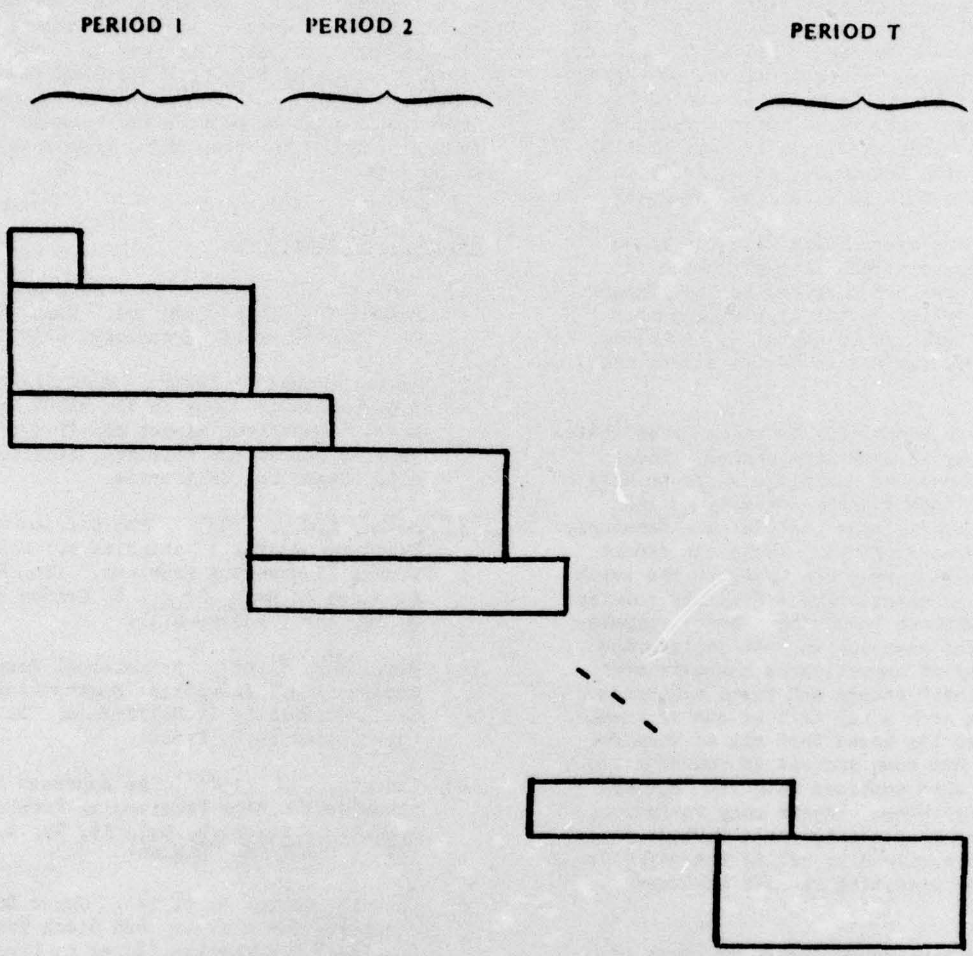

FIGURE 2. The Staircase Structure of the PILOT Energy Model

J.A. Tomlin of SOL has experimented with a partial decoupling of time periods within a model by relaxing the intertemporal constraints. The expectation is that such a relaxation will result in a more easily solvable model, whose solution can be used as a starting point for the real model, using some "gradual" approach to restore the intertemporal constraints. As might be expected, the results of this approach are quite problem dependent, and sensitive to the degree and the kind of relaxation employed. It appears that tightly constrained economic planning models, of the type available to us for these experiments, require a more sophisticated approach. Other types of staircase models are being acquired to further test this idea.

One of the more promising methods that have been investigated for reducing solution time for dynamic models involves several modifications to the simplex method designed to take advantage of the special properties and behavior of such models. The essential property of interest is the tendency of the same type of activity to be basic over several successive time periods. It therefore seems desirable to introduce a profitable type of activity in as many time periods as possible simultaneously. To do this M.A. Saunders and J.A. Tomlin have explored variants of the reduced-gradient method (a nonlinear programming algorithm already implemented by Murtagh and Saunders in MINOS [14]) on these linear problems to change several nonbasic variables simultaneously, in

contrast to the standard simplex method which changes only one nonbasic variable at a time. To ensure that the correct nonbasic variables are used, a "special pricing" technique is employed. When the problem is read in, similar activities in different time periods are identified (from the column or variable names) and linked by a circular list. Thus when an activity is priced out and found to have a favorable gradient, the corresponding vectors in other time periods can be easily found and examined, and, if satisfactory, included as candidates to be changed. It is then possible to make a step which introduces an activity in several successive time periods simultaneously.

Preliminary experiments with the above approach have led to a reduction of 20-30% in Phase II iterations when compared to the standard simplex method applied to the type of economic planning models referred to above. It is clear that many tactical variations of the scheme need to be studied.

If it is advantageous to bring in an activity simultaneously in many time periods, then, conversely, it should be advantageous to be able to also force an unprofitable activity to its lower bound in several time periods simultaneously. This is rather more difficult, since one cannot tell whether a whole group of variables can reach their bounds while maintaining a feasible solution (at least, not without incurring a heavy computational cost). The approach we have implemented identifies groups of unprofitable nonbasic activities close to their bounds and forms a direction vector scaled in such a way that if one of these variables reaches its bound then all of them do. This method has had some success in reducing the iteration count when combined with the "special pricing" described above. Again many variations are possible, and very considerable further experimentation is required to refine the methodology and expand on the promising results achieved so far.

While we have concentrated on means of improving the solution path (iteration count) above, another means of improving solution techniques for staircase models is to speed up each step of the simplex algorithm by taking advantage of the special structure of the basis for such problems. As early as 1954, G.B. Dantzig [6] pointed out that such problems exhibit an "almost" square block-triangular basis structure which could be decomposed into a product of a true square block-triangular matrix and another matrix with only a few columns differing from the unit matrix. The advantage of this procedure is that square block-triangular matrices can themselves be very efficiently decomposed to give a very sparse factorization of the basis. A version of this method, employing modern factorization techniques, has been implemented at SOL by A.F. Perold (a graduate student) and is now being tested on problems of significant size. Early indications are that this method of handling the basis can indeed be more efficient than a direct treatment which does not take the staircase structure of models into account. Perold's code is based on SOL's LPM1 linear programming code, as was the nested decomposition code by J.K. Ho and A.S. Manne [12] for the same class of problems. This should facilitate comparison between the specialized simplex and decomposition approaches to these models.

An alternative to all of the above numerical treatments of discrete multi-time-period models is to attempt to solve the underlying continuous time problem, which can be thought of as a linear control problem with state-space constraints. G.B. Dantzig and R.E. Davis are investigating a "continuous simplex method" for such problems. Although progress has been made, much work remains to be done.

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This report gives an overview of some of the work being done at the Systems Optimization Laboratory.